2016

Environmental Impact Analysis of Soybean Oil Production from Expelling, Hexane Extraction and Enzyme Assisted Aqueous Extraction

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Keywords
Carbon dioxide emission, Environmental impact, Expelling, Hexane extraction, Enzyme assisted aqueous extraction process (EAEP)

Disciplines
Agriculture | Bioresource and Agricultural Engineering | Environmental Indicators and Impact Assessment | Food Processing

Comments
This paper is from 2016 ASABE Annual International Meeting, Paper No. 162459781, pages 1-17 (doi: 10.13031/aim.20162459781). St. Joseph, Mich.: ASABE.. Posted with permission.

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An ASABE Meeting Presentation
DOI: 10.13031/aim.20162459781
Paper Number: 162459781

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2016 ASABE Annual International Meeting

Sponsored by ASABE

Orlando, Florida

July 17 – 20, 2016

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In the industry, expelling and hexane extraction are the two typical processes for soybean oil production. However, the low efficiency and hazardous chemical problem are the main issues for these two processes respectively. Enzyme assisted aqueous extraction process (EAEP) is applied to increase the efficiency without using organic solvent, which is replaced by water. The environmental impact analysis of these three processes are based on their mass flows, energy consumption and global warming potential. For mass flows, the environmental impact indices were calculated based on mass balance of input and output components. Energy consumption was used to evaluate the carbon dioxide and greenhouse gas (GHG) emissions. According to results, hexane extraction has the highest environmental impacts due to the application of organic solvent; EAEP has the highest CO_2 and GHG emissions because of more requirements for soybean flaking processes.

Keywords. Carbon dioxide emission, Environmental impact, Expelling, Hexane extraction, Enzyme assisted aqueous extraction process (EAEP)

Introduction

Soybean, the most common resource of oilseeds in the world, takes around 60% of oilseeds production (SoyStats, 2015) and contains about 20% oil content (Bernardini, 1983). In industry, the process of oil extraction from typically applies mechanical pressing process, expelling (Sawada et al., 2014), and organic solvent extraction with hexane (Hammond et al., 2005). However, the lower oil recovery from expelling, and the safety and environment issues (Li et al., 2004, Oliveira et al., 2013) resulted from solvent extraction are main challenges in soybean oil industry. For improving the oil yield and mitigating the flaws caused by expelling and solvent extraction, the enzyme assisted aqueous extraction process (EAEP) might be the novel method in industrial scale applications (Rosenthal et al., 1996).

During soybean oil extraction (Fig. 1), crops need to be cleaned, cracked, dehulled and conditioned first before the extraction process. These treatments are mainly used to break the cell wall structure of oil body and denature the protein which can improve free oil released (Lamsal et al., 2006). In extraction steps, heat and pressing were applied in expelling process to release free oil; hexane was commonly used as the solvent by its solubility with oil to extract oil from crushed meal, and the desolvenization was used to recover free oil. As to aqueous extraction, water was used as solvent with it insolubility with oil, and the oil in water emulsion was form during the extraction. Consequently, the demulsification was applied to recover free oil from emulsion. Otherwise, the aqueous extraction process also extract the protein simultaneously; therefore, the further refining processes were not required for aqueous extraction (Johnson & Lucas, 1983, Jung et al., 2009, Sekhon et al., 2015).

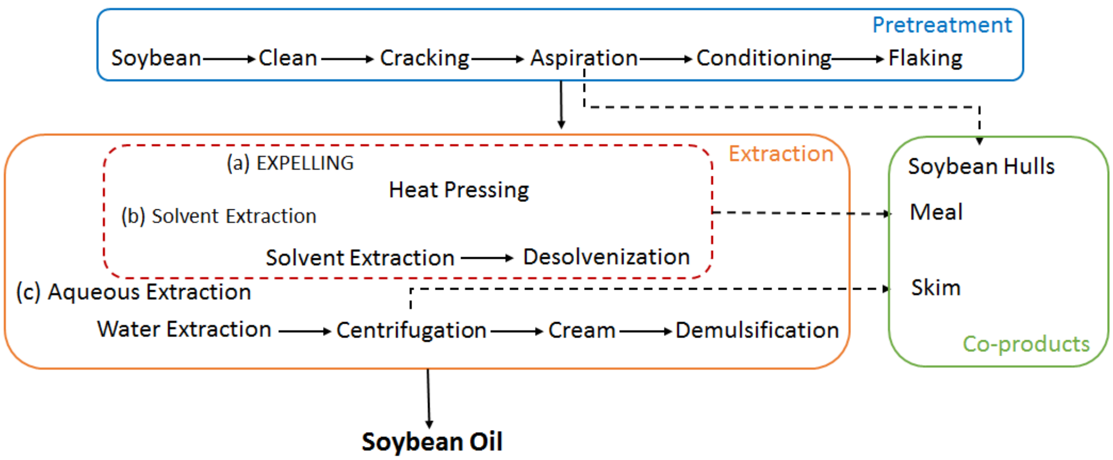

Fig. 1 Expelling, solvent and aqueous processes of soybean extraction

Besides the oil recovery and economic feasibility, the substantial environmental impact from the processes is another critical factor to evaluate different processes. Expelling, the mechanical process, mainly uses electricity in the extraction without adding chemicals; therefore, the energy consumption is the major problem. For solvent extraction, though higher oil can be recovered, the most controversial issue is the application of organic and fossil derived chemicals, which leads to critical environmental and safety issues. Additionally, the energy consumption is required for the process (Li et al., 2006). As for EAEP, water is as solvent which could mitigate the environmental impact comparing to solvent extraction. However, the demulsification has been seen as a critical step for oil recovery in aqueous extraction due to its high energy requirement especially on physical (Hagenmaier et al., 1972, Harada & Yokomizi, 2000, McClements, 2005) and chemical methods (Menon & Wasan, 1985).

According the different extraction processes, the environmental impact analysis (EIA) could be the tool to quantify their energy, materials, and products flows to calculate energy consumption and potential greenhouse gas and pollutants emissions during oil producing processes (Salomone & Ioppolo, 2012). Heinzle et al., (1998) proposed the quntifiying methodology to evaluate the environmental impacts derived from chemical processing by calculating all input and outout components. Also, the Organization for Economic Co-operating and Development (OECD) proposed the environmental indicator to assess the sustainability of industrial processing in 2001. However, there were few studies manily focused on soybean oil production especially comparing different processes and the alternative extraction methodology.

This study mainly focuses on the comparison among these three extraction processes. The EIA is divided into two sections including environmental impacts derived from material flows of the process and the energy consumption required by processing. Additionally, the environmental impacts will be quantified based on material balance of the whole process which evaluated the impact derived from input and output. For energy consumption, the electricity, and heating resource such as natural gas and steam were converted into carbon dioxide emission and greenhouse gas emission potential. According these criteria, the environmental feasibility could be obtained.

Materials and Methods

1. Environmental Impact

The environmental impacts are based on the input and output components, and these indexes are also calculated by mass balance of the process. The expelling and hexane extraction were based on research from (Haas et al., 2006); and, the EAEP was evaluated based on (de Moura et al., 2011). The input components, output components and the mainproduct are shown in Table 1 with their amounts. These amount were the bases for the further environmental indices calculations.

Table 1 The mass flow of input and output components

		Mass flow (kg/hr) by each process		
Components	Input/Output (I/O)	Expelling	Hexane	EAEP
Soybean	I	24278.18	24278.18	11250
Hexane	I	N/A	21554.72	N/A
Water	I	1895.75	3068.63	59895
NaOH	I	N/A	N/A	67
Protex 6L	I	N/A	N/A	106.5
Solid Wasted	O	72.84	72.49	1468.20
Water	O	2397.02	1021.92	N/A
Sewage	O	311.02	1295.52	N/A
Hexane	O	N/A	23219.20	N/A
NaOH(aq)	O	N/A	N/A	4700.93
Soybean Hulls	O	801.28	805.86	733.55
Soybean Meal	O	19047.10	18108.48	N/A
Skim	O	N/A	N/A	54571.81
Insoluble Fiber	O	N/A	N/A	7595.52
Protex 6L	O	N/A	N/A	106.5
Soybean Oil	Main Product	3214.15	4374.24	2141.99

1.1 Boundary Definition

The boundary of soybean oil extraction includes oilseed pretreatment, extracting processes, oil refining and coproducts handling, and the transportation was not considered (Fig. 2). Additionally, the land use and the generation of natural gas and the electricity were not considered in this EIA as well. However, the steam used as heating resource in oil extraction processes was assumed to be produced by the boiler within the plant and natural gas was the resource. Therefore, the boundary can be seen as the producing plant.

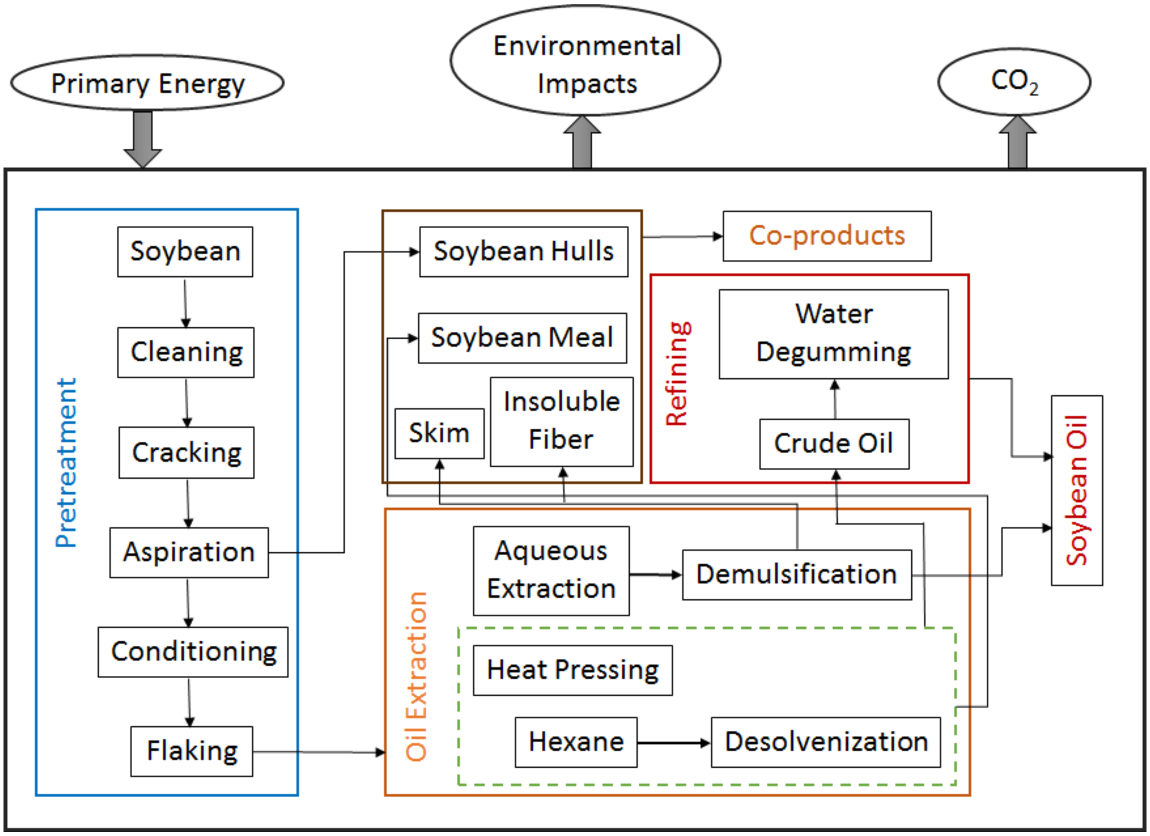

Fig. 2 Boundary of soybean oil extraction

1.2 Components Classification

For the environmental impacts, they were divided into input and output components, and there four impact groups for each component individually. Also, there were several categories were set up for each impact group respectively (Heinzle et al., 2006). The hierarchical diagram of EIA is shown in Fig. 3.

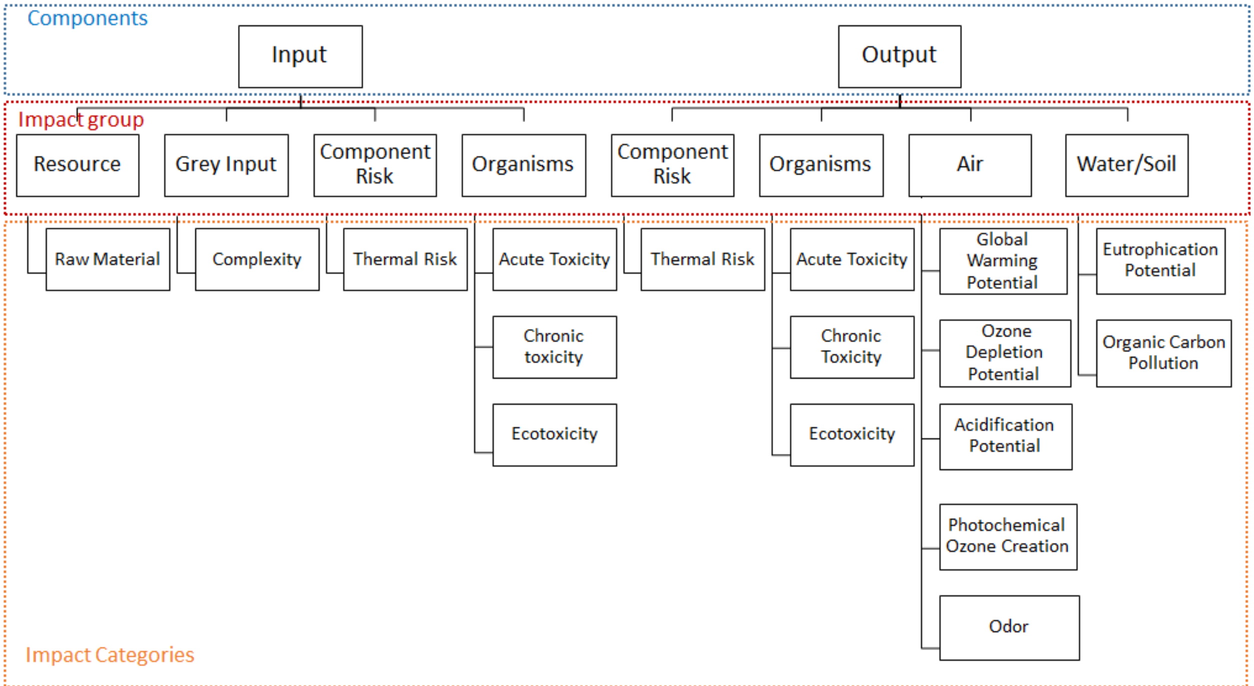

Fig. 3 Hierarchy of environmental components and impacts (Heinzle et al., 2006)

As the hierarchy of environmental components, groups and categories were built, the impcat categories were allocated into three classifications (A, B and C) based on how what levels of enviromental impacts caused by each component in the process (Table 2). The highest classification in the referred impcat cataegories defined the class of impact groups. For impact category classification, critical chemical used and complexity were based on Ullmann's Encyclopedia of Industrial Chemistry (Ullmann, 1985); thermal risk and acute toxicity were according to the study of Budavaris et al., (1989). And these categories were also referred to R-phrase, EU classification, standard system for the identification of the hazards of materials for emergency respond established by National Fire Protection Association (NFPA), CH-poison classification, German water hazard class (WGK), emergency response planning guideline (ERGP) and immediately dangerous to life or health value (IDHL) established by US National institute for Occupational Safety and Health (NIOSH).

Additionally, the air and water/soil impact groups were evaluated based on their potential numbers (Houghton, et al., 2001, UNEP, 2000, Derwent et al., 1998, Heijungs et al.,1992).

Table 2 Criteria for impact category classification

Impact Category	Class A	Class B	Class C
Raw Material Availability	Fossil derived, exhaustion with 30 years	Fossil derived, exhaustion with 30-100 years	Exclusively renewable or long term supply
Critical Material Used	Heavy metal, AOX, PCB used or produced in stoichiometric amounts	Involved in sub-stoichiometric amounts	No critical components involved
Complexity of Process	>10 stages	3-10 stages	<3 stages
Thermal Risk	R 1-4, 9, 12, 15-17, 44; EU: F^+, E; NFPA F+R: 3, 4.	R 5-8, 10, 11, 14, 18, 19, 30; EU: F, O; NFPA F+R: 2	NFPA F+R: 0, 1
Acute Toxicity	EU: T^+; R 26-28, 32; CH-poison class: 1, 2; NFPA H:4; WGK 3; ERPG: <100 mg/m^3; IDLH : <100 mg/m^3	EU: T, X_n, X_i, C; R 20-25, 29, 31, 34-39, 41-43, 65-67; CH-poison class: 3, 4; NFPA H: 2, 3; WGK 2, ERPG: 100-1000 mg/m^3; IDLH: 100-1000 mg/m^3	CH-poison class: 5; NFPA H: 0, 1; WGK 1; ERPG: >1000 mg/m^3; IDLH: >1000 mg/m^3
Chronic Toxicity	MAK: <1 mg/m^3; IARC: 1, 2A; R 45-49, 60-61, 64	MAK : 1-10 mg/m^3; IARC : 2B, 3 ; R 33, 40, 62, 63 ; EU : T, T^+, X_n ; CH-poison class : 1, 2	MAK : >10 mg/m^3; IARC: 4; CH-poison class: 3, 4, 5
Ecotoxicity	EU: N; R 50; WGK 3	R 51-58; WGK 2	WGK 1 or no water hazard
GWP	>20	<20	N/A
ODP	>0.5	<0.5	N/A
AP	>0.5	<0.5	N/A
POCP	>30 or NO_x	2-30	<2 or no effect
Odor		Threshold < 300 mg/m^3	Threshold >300 mg/m^3
EP	N-content>0.2 or P-content>0.05	N-content < 0.2and P-content < 0.05	No N and P
OCPP		ThOD>0.2g O_2/g substrate	ThOD<0.2 g O_2/g substrate or no organic compound

GWP: global warming potential; ODP: ozone depletion potential; AP: acidification potential; POCP: photochemical ozone creation potential; EP: eutrophication potential; OCPP: organic carbon pollution potential

1.3 Environmental Impact Indices

According to the classification of each impact category derived from input/output components, there were two quantifying system used for the assessment which were multiplying and averaging systems. Otherwise, the mass balance of input and output components were another factor in the assessment. First of all, these three classifications were converted into the values, which were the multipliers for environmental indices calculation. For multiplying system (Eq. 1), classes A, B and C were corresponding to values of 4, 1.3 and 1 individually. The values of 1, 0.3 and 0 were used in averaging system (Eq. 2) to substitute these three classes respectively. These values were the basis for the calculation of environmental factors (EF). Due to there were 4 impact groups for input and output components, the EF for these components were 1-256 and 0-4 for EF_{multi} and EF_{mv} individually (Heinzle et al., 2006).

$$EF_{multi} = \prod_{1}^{j} G_j \qquad Eq.1$$

$$EF_{mv} = \frac{G_1 + G_2 + G_3 + G_4}{j} \qquad Eq.2$$

Mass balance of processes was the basis to calculate mass index of input (MI_{in}) and output components (MI_{out}) based on the amount of each component (m_i) and main product (soybean oil, m_p) involved in the process (Eq. 3, 4). The process mass index (MI_p) is the summation of the MI of each component. The $MI_{p(out)}$ was less than $MI_{p(in)}$ by 1 because the main product was not considered in the total MI of output process. Furthermore, the environmental impact (EI) was define as the multiplication of EF and MI for each component (Eq. 5), and the summation of each component EI was defined as total process environmental index denoted as EI_p (Eq. 6). Consequently, the general effect impact (GEI) were calculated as the ratio of EI_p to MI_p (Eq. 7) (Heinzle, et al., 1998).

$$MI_p, in = \sum_{1}^{i} \frac{m_i}{m_p} \qquad Eq.3$$

$$MI_p, out = \sum_{1}^{i} \frac{m_i}{m_p} - 1 \qquad Eq.4$$

$$EI_i = EF_i \times MI_i \qquad Eq.5$$

$$EI_p = \sum_{1}^{i} EI_i \qquad Eq.6$$

$$GEI = \frac{EI_p}{MI_p} \qquad Eq.7$$

2. Energy Consumption

The electricity was the main energy resource for these three processes, and natural gas and steam were used as the heating reagent especially in drying, desolvenization and co-product handling processes. Based on the expelling, hexane extraction and the EAEP processes, the total primary energy consumptions were simulated and calculated by SuperPro Designer v9.0 (Intelligen, Inc., Scotch Plains, NJ).

The energy consumption during the processes were converted into carbon dioxide (CO_2), carbon monoxide (CO), volatile organic compound (VOC), nitrogen oxide (NOx), sulfur oxide (SOx), methane (CH_4) and nitrous oxide (N_2O) emissions by multiplying the conversion factors (Table 3). These values the potential amounts of GHG emissions required to product sufficient energy for oil extraction processes.

3. Table 3 Conversion factors for energy required in oil extraction processes

GHG	Steam (1MJ)	Electricity (1kwh)	Natural Gas (1tonne)
CO_2	78.30 g	0.55 kg	219.57 kg
VOC	15.27 mg	57.03 mg	0.29 kg
CO	67.69 mg	0.15 g	0.54 kg
NOx	96.49 mg	0.37 g	0.75 kg
SOx	14.26 mg	1.08 g	0.51 kg
CH_4	0.25 g	0.92 g	4.62 kg
N_2O	2.10 mg	8.60 mg	1.54 g
Citation	(Clark et al., 2011)	(Cai et al., 2012)	(Clark et al., 2011)

Results and Discussion

1. Environmental impacts

1.1 Input components

1.1.1 Classification of impact groups and categories

According to the classification of impact groups and categories for input components, the results are shown in table 4. In resource group, the hexane extraction was allocated to class B due to the application of organic solvent; however, other processes were using bio-derived materials such as water in expelling, and enzyme, water and small amount of NaOH, which was not involved in stoichiometric production, in the EAEP. For grey input, all processes were undergoing oilseeds pretreatment, extraction, degumming/demulsification and coproducts handling at least 3 steps; therefore, they all belonged to class B.

For component risk and organism group, the hexane is the main reason for solvent extraction to be allocated to class B. Based on hazard profile, hexane has thermal risk, acute toxicity and ecotoxicity due to its R-phrase of 11, 20, 51, 53, 65 and 67, and NFPA F:3. Hence, these three categories were allocated to class B. Otherwise, it also has class A of chronical toxicity due to the R-phrase of 48 (Hexane, 2016). As to EAEP, owing to the application of NaOH, the agent used to adjust the pH during the extraction, it led to acute toxicity and was allocated into class B due to its R-phrase of 35 (Sodium Hydroxide, 2016). Contrary to these two processes, all impact categories of expelling were all in class C because it is the mechanical process without adding any chemical in the process.

Table 4 Classification of impact groups and categories for input components

Impact Group	Impact Category	Expelling	Hexane	EAEP
Resources	Raw materials	C	C	C
	Critical materials	C	B	C
Grey input	Complexity	B	B	B
Component risk	Thermal risk	C	B	C
Organism	Acute toxicity	C	B	B
	Chronic toxicity	C	A	C
	Ecotoxicity	C	B	C

1.1.2 Environmental impact indices of input components

According to the calculations the mass index for each component, the results (Fig. 4) reflect the conditions of materials applications for each process. Again, expelling, hot pressing, only used water in dugumming process. Hexane, used in solvent extraction has the better efficiency for extraction. EAEP has the highest mass index among these three processes because large amount of water used in extraction to form the oil in water emulsion.

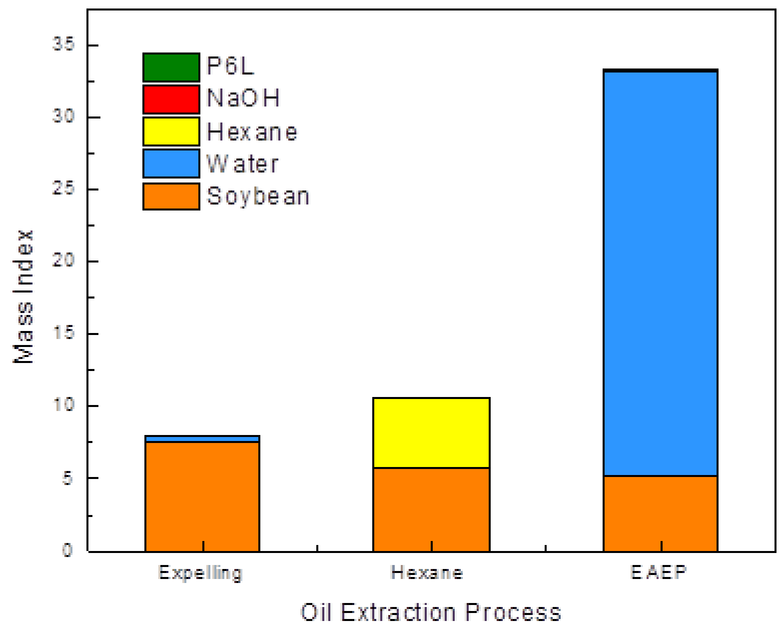

Fig. 4 Mass index of input components

Based on the calculations of EFs and Mis, two systems (multiplying and averaging) were conducted (Fig. 5). From the results, hexane extraction has the highest EI in both calculation systems, and the reason is the application of large amount of hexane in the process. However, as these two calculation systems were compared, the components without environmental impacts were also considered; for averaging system, it only calculated the components with thermal and organism risks. And these conditions can be observed from the quantification of the different classes of impact categories. Thus, form the results of EI of averaging system, the components with environmental impact potential are easier to be observed. For hexane extraction, hexane is the only chemical used in the process, but it still results in highest EI due to large amount of application, and the ratio to oilseeds is around 1. As to EAEP, though NaOH has the potential to environmental risk, it was used as the agent to adjust pH for extraction. In the aspect of enzyme (P6L) used in EAEP, the bio-derived enzyme also gives to EI due to its producing processes and nitrogen and sulfur contents.

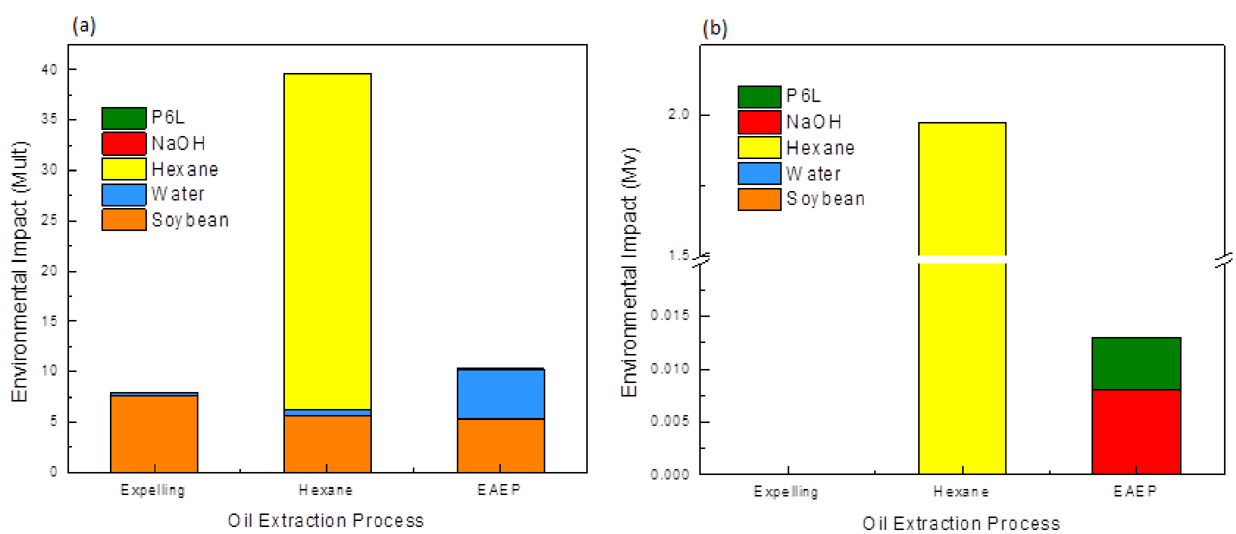

Fig. 5 Environmental impact of input components. (a): multiplying system; (b): averaging system

As the EI of each component were calculated, the GEI can be obtained, and that is regarded as the index for evaluating the environmental impact potential for the process. According to the results (Fig. 6), hexane extraction process has the highest general impact potential than others in both systems. For EAEP, it has almost the same impact potential as expelling; however, the significant difference can be observed from the averaging system which is because the averaging system doesn't take the components without environmental impact into consideration.

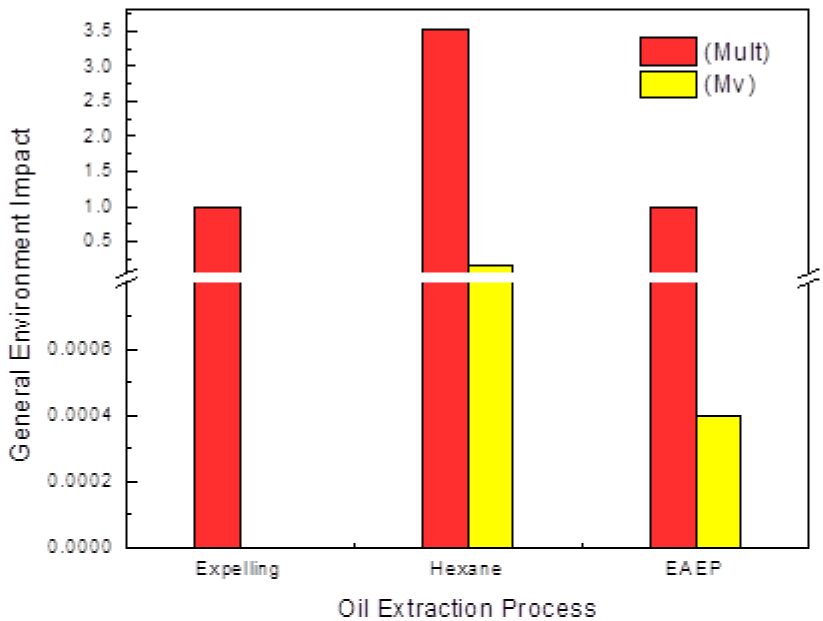

Fig. 6 General environmental impacts of input components

1.2 Output components

1.2.1 Classification of impact groups and categories

Table 5 shows the classification of impact categories for output components. In component risk and organisms groups, the results are as same as input components due to the hexane emission for the solvent extraction and the wasted NaOH present in EAEP. However, hexane has no GWP, ODP, AP and POCP (TRACI 2.1, 2014), also NaOH solution used in EAEP has the same results as solvent extraction.

In water/soil group, all processes produce solid wastes, sewage which consists of protein, carbohydrates and lipids. Therefore, they have impact potential and are allocated into class B.

Table 5 Classification of impact groups and categories for output components

Impact Group	Impact Category	Expelling	Hexane	EAEP
Component risk	Thermal risks	C	B	C
Organisms	Acute toxicity	C	B	B
	Chronic toxicity	C	A	C
	Ecotoxicity	C	B	C
Air	Global warming potential	C	C	C
	Ozone depletion potential	C	C	C
	Acidification potential	C	C	C
	Photochemical potential	C	C	C
	Odor	C	C	C
Water/Soil	Eutrophication potential	B	B	B
	Organic carbon pollution	B	B	B

1.2.2 Environmental impact indices of output components

According to the products, co-products and wastes produced by each process, the mass index of output components are shown in Fig. 7. Soybean meal is the main co-product of expelling and hexane extraction; however, the hexane is still the critical factor for solvent extraction even the countercurrent and continuous system was used to reduce the total amount.

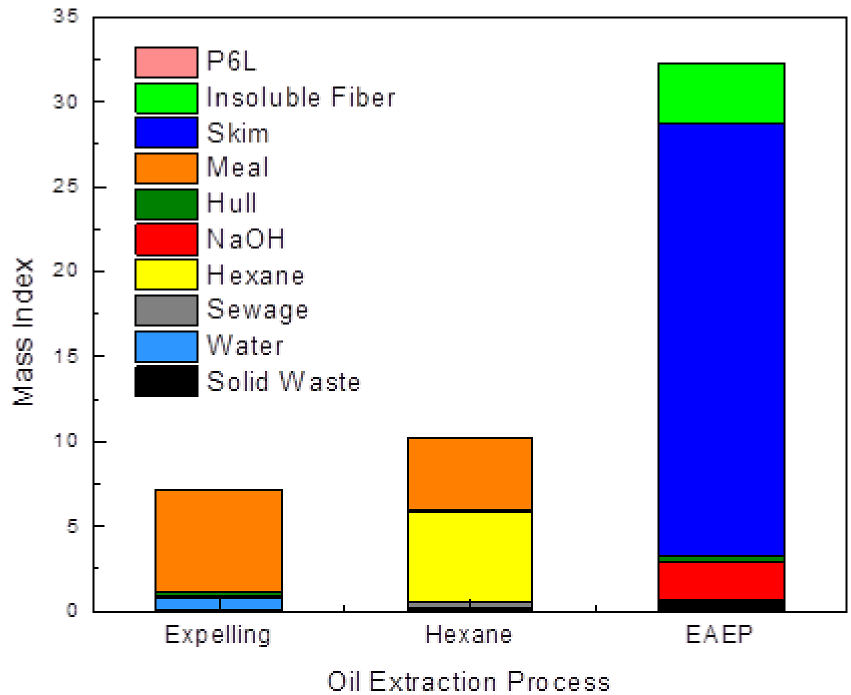

Fig. 7 Mass index of output components

For EAEP, the skim produced by the centrifugation of the emulsion after aqueous extraction takes the majority of total MI. Additionally, the insoluble fiber and NaOH are another two critical components for EAEP. These results also indicates the proper strategy for the co-product and waste handling is essential for EAEP to decrease final environmental impacts due to its highest MI. Therefore, the skim and insoluble were proposed to be used as another materials to produce ethanol in the integrated system combined with corn based ethanol production system. Otherwise, these co-products were claimed to increase the ethanol yield in corn based bioethanol production with synergetic effect, and that also increase the potential of EAEP application in industry (Sekhon et al., 2015).

Two systems of EI calculations were conducted for output components as well (Fig. 8). From the results, EAEP has the highest EI in both systems, and the skim is the dominant factor for the output components due to its large amounts of production. Hexane still shows the large effects on solvent extraction. For expelling process, the co-products, soybean meal and hulls are main resources of EI; however, they can also be regarded as the products of the process, hence there is no other factors having impact potential derived from expelling process.

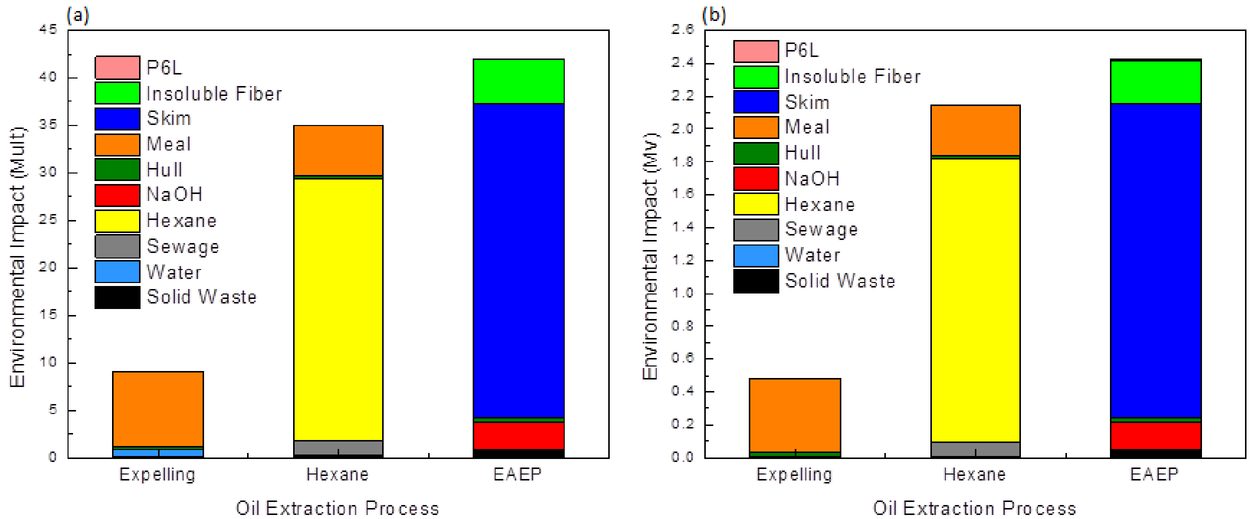

Fig. 8 Environmental impact of output components (a): multiplying system; (b): averaging system

From the aspect of general environmental impact (Fig. 9), hexane extraction still gives to the highest general impact potential though it has the lower EI. However, because the presence of hexane in the extraction process which has higher component and organism risks and these factors leads to the higher final scores in GEI.

For EAEP and expelling processes, the trend of results is similar to input component. Otherwise, the results from averaging system are much closer than input components due to the co-product effects. Therefore, according to the results of input and output components, the expelling is the cleanest process due to no addition of chemicals, and the EAEP could mitigate the environmental impact potential by substituting hexane with water.

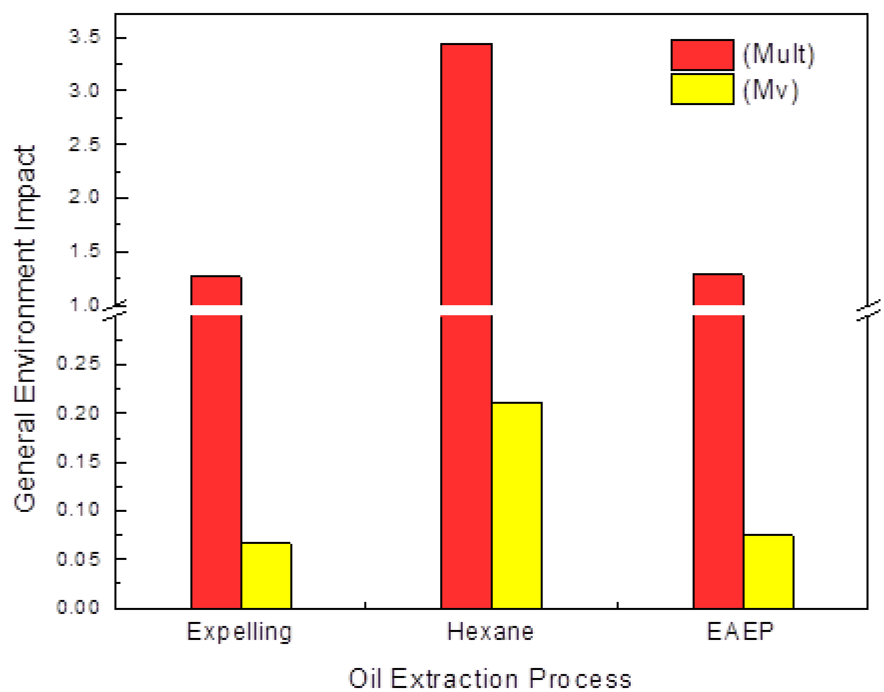

Fig. 9 General environmental impacts of output components

2. Energy consumption

2.1 Primary energy requirement

According to the soybean oil annual productivity, the energy requirements for producing 1 kg of soybean oil are shown table 6. From the results, the EAEP has the highest electricity consumption during the processing. For hexane extraction, large amounts of steam were required due to the desolvenization; and the high electricity requirement was essential for expelling process.

Table 6 Energy requirements for 1kg soybean oil production

Processes	Steam (KJ)	Electricity (kwh)	Natural Gas (kg)
Expelling	0.98	1.26	0.16
Hexane	3.07	0.97	0.18
EAEP	1.85	3.32	n/a

The whole extraction process were divided into three main steps including pretreatment, extraction and post handling for these three processes. And, the electricity allocation of these three main steps are represented in Fig. 10. According the results, the pretreatment takes over 70% of total electricity consumption, and the EAEP has over 90% of electricity consumption for the pretreatment. The pretreatment includes oilseeds cleaning, drying, cracking, flaking and tempering. For EAEP, the cracking, flaking and extrusion are required to break down the cell wall structure to improve the formation of oil in water emulsion (Jung et al., 2009); therefore, the intense electricity requirement for pretreatment can be observed. Otherwise, expelling process has the highest electricity consumption in extraction; and hexane process has the highest electricity consumption in posthandling among these three processes. These results also reflect that expelling has lower oil extraction efficiency and the solvent extraction needs more energy for post handling indicating the requirement for desolvenization. By contrary, the EAEP has the lowest electricity in post handling because it's able to separate oil and protein simultaneously and there is no meal production during the process.

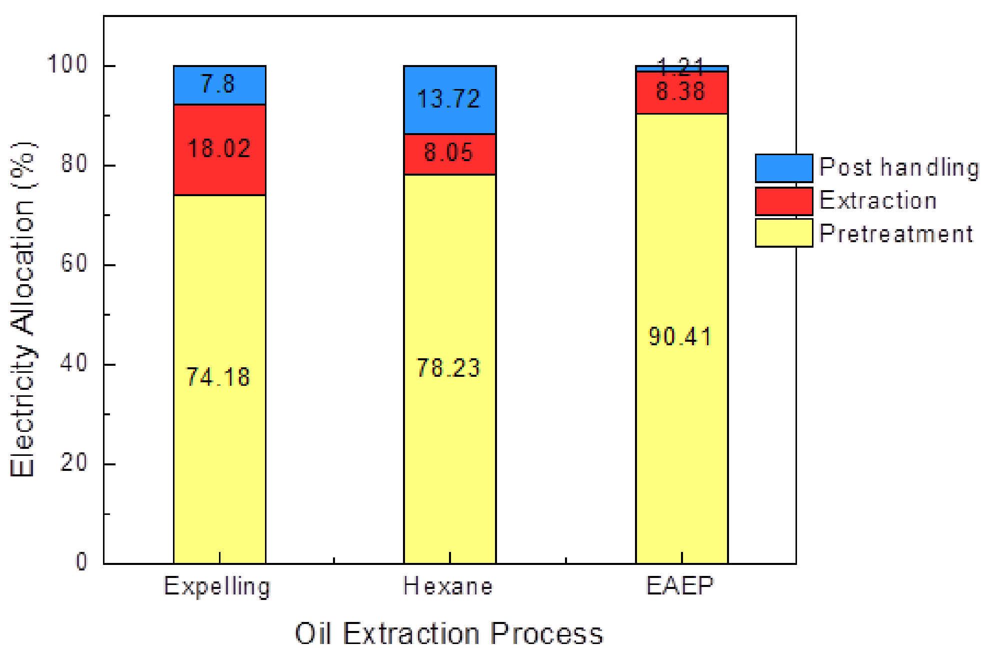

Fig. 10 Electricity consumption for oil extraction processes

2.2 GHG emissions

According to the primary energy consumptions for three oil extraction processes, the GHG emission were calculated based on 1 kg of soybean oil production, and the results are shown in Fig. 11.

From the results, hexane extraction has the lowest GHG emissions among these three processes. And, that also indicates the hexane extraction has the highest oil recovery rate about 97%, and it is the most energy efficient approach for oil extraction though the large amounts of steam are required for desolvenization. Therefore, that could be the reason that the solvent extraction is the most common method used in industry. For expelling process, the intense energy requirement for the pressing is the main reason to lead to higher GHG emission. Additionally, the results reflect the expelling has lower oil recover than solvent extraction, and that is the main disadvantage of the mechanical processes (Li et al., 2004).

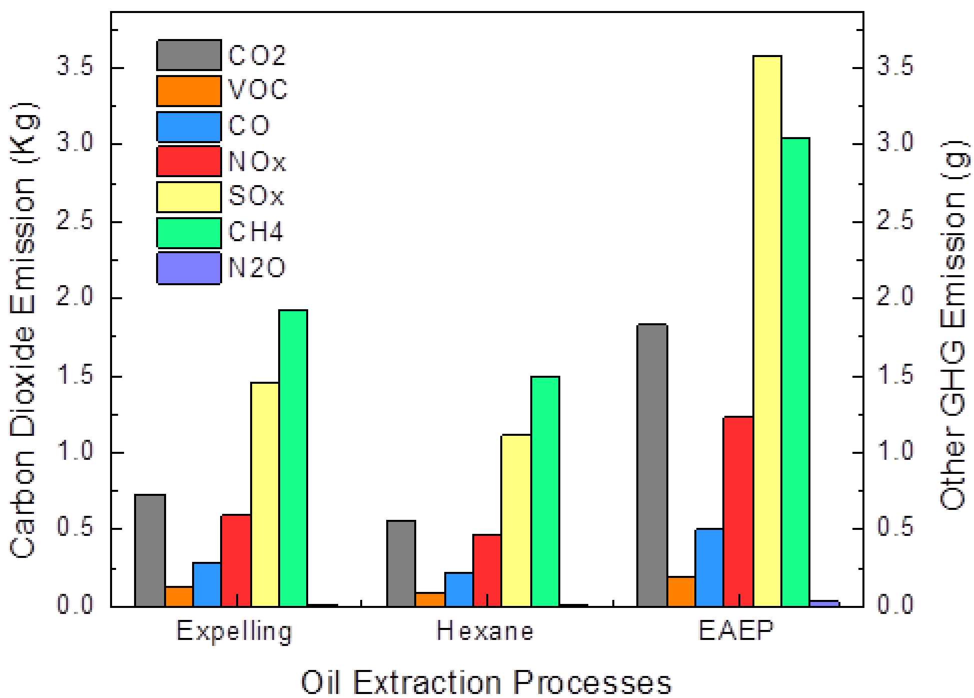

Fig. 11 GHG emissions of three oil extraction processes

As to EAEP, the electricity consumption in pretreatments is the driving force to lead the highest GHG emssions especially CO_2 emissions, which is about three times higher than hexane extraction. The finer soybean flakes were produced, the more oil recovery efficiecy were obtained which could achieve over 80% due to the larger surface area and more efficiency of emulsion formation and . Although the enzyme was used to assist the demulsification which could reduce the energy consumption at some level (Lamsal et al., 2006, Jung et al., 2009), the amount of energy consumption reduced by applying enzyme has limited ability to compensate the energy consumption in pretreatment. As more energies are required, the GHG emissions would be increased consequently. These results indicate not only the operaing costs, but the intense energy requirement is another criticl hurdle for EAEP to be used in industry.

Conclusions

From the results of environmental impacts, energy consumption and GHG emissions, that reproves expelling is the cleanest approach for oil extraction, but it has worse energy efficiency and higher GHG emissions than solvent extraction; however, although hexane extraction is the most energy efficient and has the lowest GHG emissions, it has the highest environmental impact potential. For EAEP, it has been seen as an alternative to reduce the environmental impacts and also to maintain the high oil recovery. Obviously, the EAEP lowers the environmental impacts and the GEI values are pretty close to expelling process. However, the highest energy consumption is required to produce finer soybean flakes to improve oil recovery which leads to the highest GHG emissions. Thus, this is till the challenge for EAEP to be used in industry practically.

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